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ORIGINAL

# A Guidance Manual for the Input of Biological Information to Water Intake Structure Design

Fish and Wildlife Service

U.S. Department of the Interior

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# A GUIDANCE MANUAL FOR THE INPUT OF BIOLOGICAL INFORMATION TO WATER INTAKE STRUCTURE DESIGN

D. A. Neitzel
M. A. Simmons
D. H. McKenzie

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Pacific Northwest Laboratory
Richland, Washington 99352

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# PREFACE

Entrainment and impingement of aquatic organisms are two of the most visible environmental impacts associated with the operation of water intake structures. Often, the design and location criteria for water intake structures do not include biological information that could reduce entrainment and impingement impacts, and some methods employed at electrical power plants to reduce these impacts have a number of inherent problems (Reynolds 1980). An example of the latter includes off-stream cooling facilities such as cooling towers, cooling ponds, and spray canals at electrical power generating plants. A study conducted by the National Power Plant Team of the U.S. Fish and Wildlife Service (NPPT 1978) indicated that decisions affecting intake structure design and location are made before biological consequences are assessed. If biological information could be included in design and location decisions for water intake structures, potential for entrainment and impingement of organisms would be reduced. In the case of electrical power generation, diminished entrainment and impingement impacts could permit the use of more cost effective once-through cooling systems. The U.S. Fish and Wildlife Service has determined that information on fish and shellfish behavior and physiology is most necessary to intake design (U.S. Fish and Wildlife Service 1978).

This manual provides guidance to the biologist who is asked to provide biological input to a water intake design. The manual provides examples of types of biological information that might be included in intake design. Procedures for quantifying biological information and defining specific tasks that will generate quantifiable data are discussed. Procedures described are applicable both to new structures and modified existing structures.

## ORGANIZATION OF THE MANUAL

This manual is a summary of the reports, "A procedure for the input of biological information to the design, location, or modification of water intake structures," and "Evaluation of models for developing biological input for the design and location of water intake structures." These reports detail two of the three major facets of the procedure outlined in this manual. Only major points of these reports are repeated here; some examples are used for illustrative purposes.

The first section of this manual briefly introduces the three facets of the process developed to provide biological information to intake designers. How the facets are interrelated and how information should flow into the intake design are discussed. The section entitled FACETS OF THE PROCESS FOR INCLUDING BIOLOGICAL INFORMATION IN WATER INTAKE STRUCTURE DESIGN, details how the facets should be approached by a biologist/user. The next section of the manual presents data from two sites to illustrate application of the process (SITE-SPECIFIC EXAMPLES). Those data that are most likely unavailable to biologists required to provide input to intake design are discussed in the final section (FUTURE RESEARCH). References used in the manual are listed in LITERATURE CITED. The reader is directed to the reports mentioned at the beginning of this discussion for more information. Those reports include listings of references useful to biologists using the procedure outlined in this manual.

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# INTRODUCTION

A biologist's ability to prepare input to the design, location, or modification of a water intake structure will be enhanced when biological information can be described quantitatively. Quantitative information can be modeled so design engineers can predict the impact of alternate intake operations on indigenous biological communities. The purpose of this manual is to outline procedures for providing a design engineer with biological information that can reduce impacts of water intake structures on aquatic resources.

The initial body of biological information available to intake designers is very general. The biologist should be responsible for reviewing this information and reducing it to features relevant to the design engineer (Table 1). The process of identifying biological information needed and the methods and procedures for applying this information in design, location, or modification of water intake structures is multifaceted and iterative (Figure 1). The three facets of the process discussed in this manual are illustrated as balloons in Figure 1. The information generated in each facet has application to the other facets. Interrelationships are illustrated with connecting arrows.

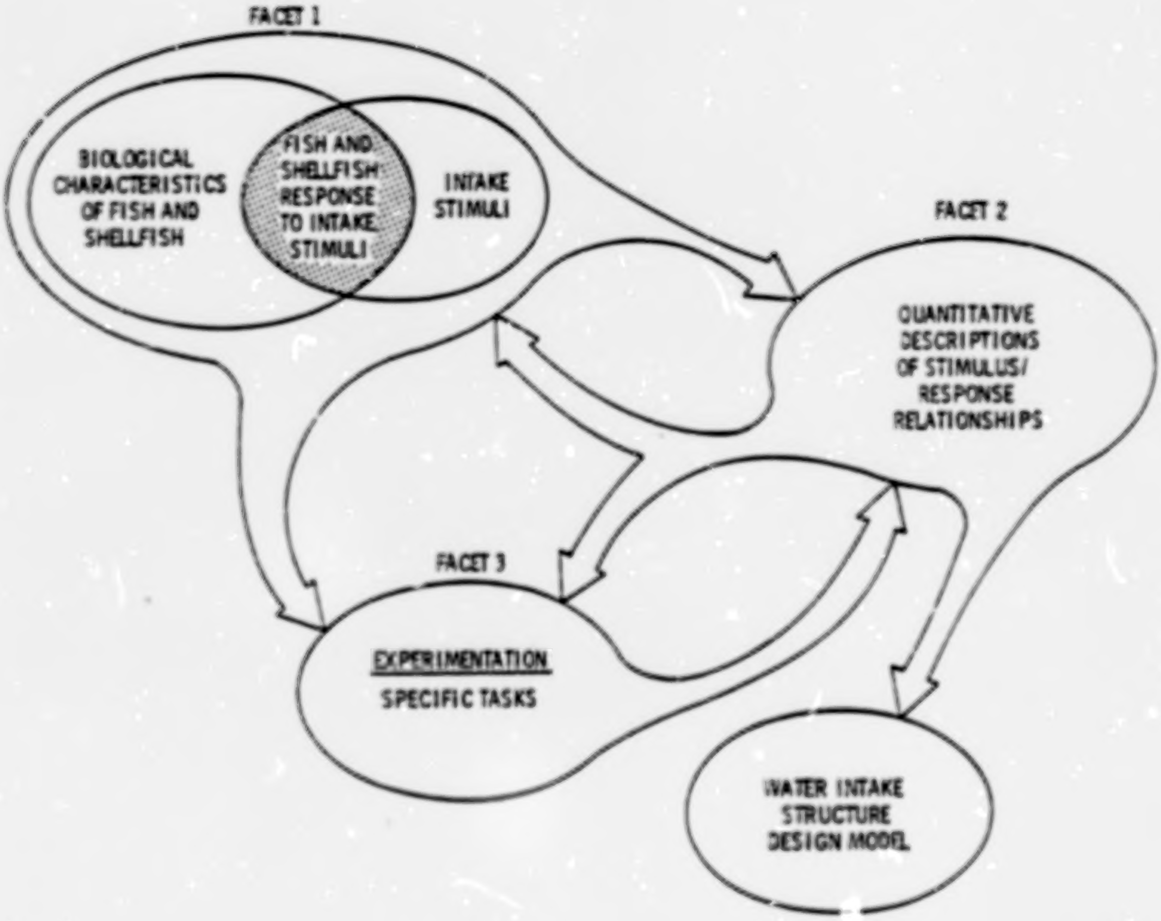
The first facet of the process includes three steps: 1) organization of biological information, especially behavioral and physiological responses of fish and shellfish, that influence vulnerability to entrainment and impingement, 2) identification of water intake stimuli, and 3) descriptions of intake stimulus/biological response relationships. It is the stimulus/response relationships that need to be quantified for inclusion in water intake designs.

In the second facet of the process, quantified descriptions of stimulus/response relationships are generated. Quantifying stimulus/response relationships can 1) provide direct input to water intake design, 2) suggest the need for experimentation, or 3) help clarify stimulus/response relationships.

The third facet of the process, experimentation and data analysis, helps define specific tasks or experiments that can be used to generate data for quantifying stimulus/response relationships. Specific tasks designed to provide data may be suggested by the stimulus/response descriptions or as a result of quantifying these relationships.

Table 1. Examples of General Biological Information and the Reduction Process for Defining Site-Specific Information to Reduce Entrainment and Impingement Impacts

| General Biological Information | Site-Specific Information to Reduce Entrainment and Impingement Impacts | Biological Criteria For Environmentally Acceptable Design |
|---|---|---|
| fish and shellfish distribution | distribution of fish and shellfish during life-stage vulnerable to entrainment and impingement | intake location and operation apart from vulnerable fish and shellfish |
| swim speed | swim speed/entrainment and impingement velocities related to species fatigue | intake velocity that does not fatigue fish and shellfish near structure |
| rheotactic response | intake velocity, current direction/rheotactic response relationships | current velocities and directions that do not attract fish and shellfish |
| reefing response | design that affects reefing response of fish and shellfish | structural design that repels fish and shellfish or attracts fish and shellfish away from areas where fish might become entrained or impinged |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EXPERIMENTATION
SPECIFIC TASKS
WATER INTAKE STRUCTURE DESIGN MODEL

Figure 1. Process for inclusion of biological information into water intake structure design.

# FACETS OF THE PROCESS FOR INCLUDING BIOLOGICAL INFORMATION IN WATER INTAKE STRUCTURE DESIGN

## ORGANIZATION OF BIOLOGICAL AND INTAKE INFORMATION

The organization of biological and intake information (Figure 2) includes three steps. First, relevant fish and shellfish behavioral, physiological, and ecological characteristics that influence the degree of vulnerability to entrainment and impingement must be identified. Second, water intake structure stimuli that elicit biological responses must be named. Finally, the stimulus/response relationships must be described. The dotted, overlapping section of Figure 2 is presented to emphasize that only relevant stimulus/response relationships should be used in following facets of the process. Examples for each of the three steps of the first facet of the process are presented to help the user of the manual think about the types of relationships that are useful at specific intake sites.

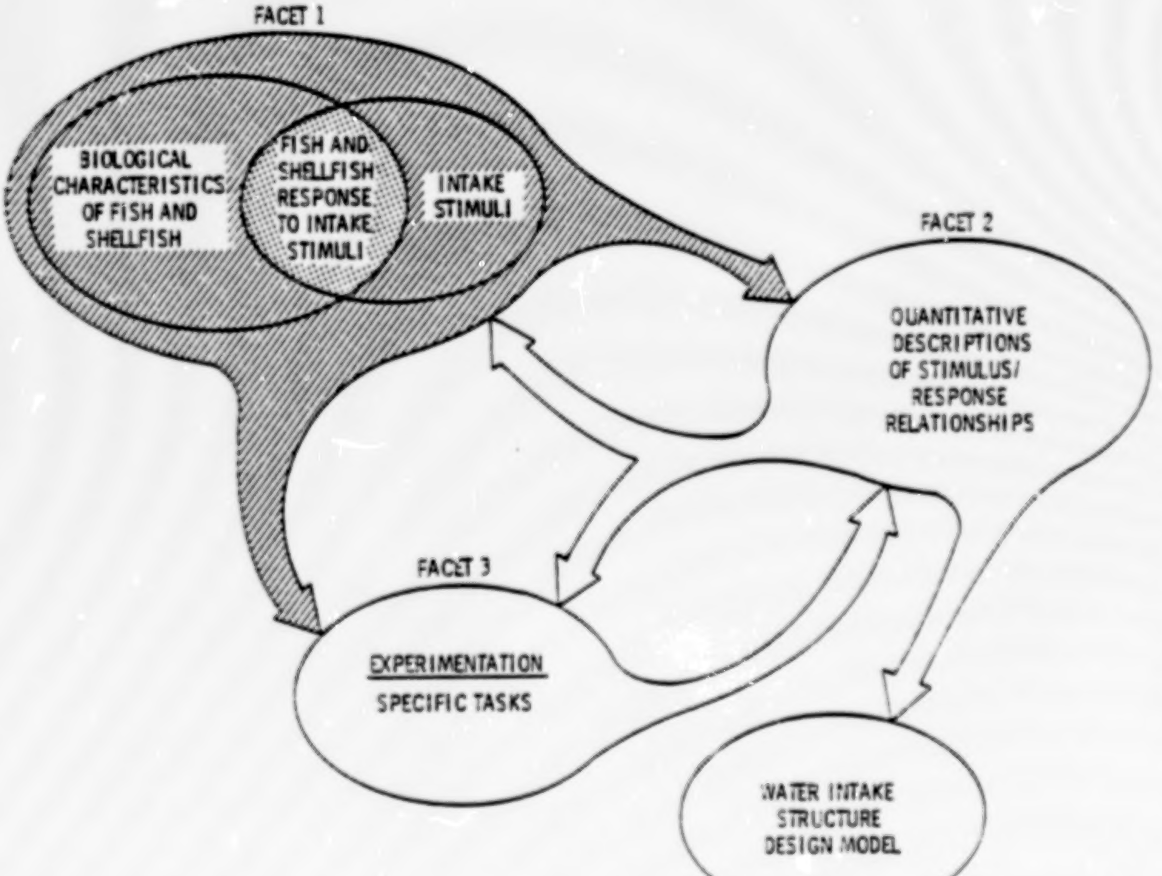
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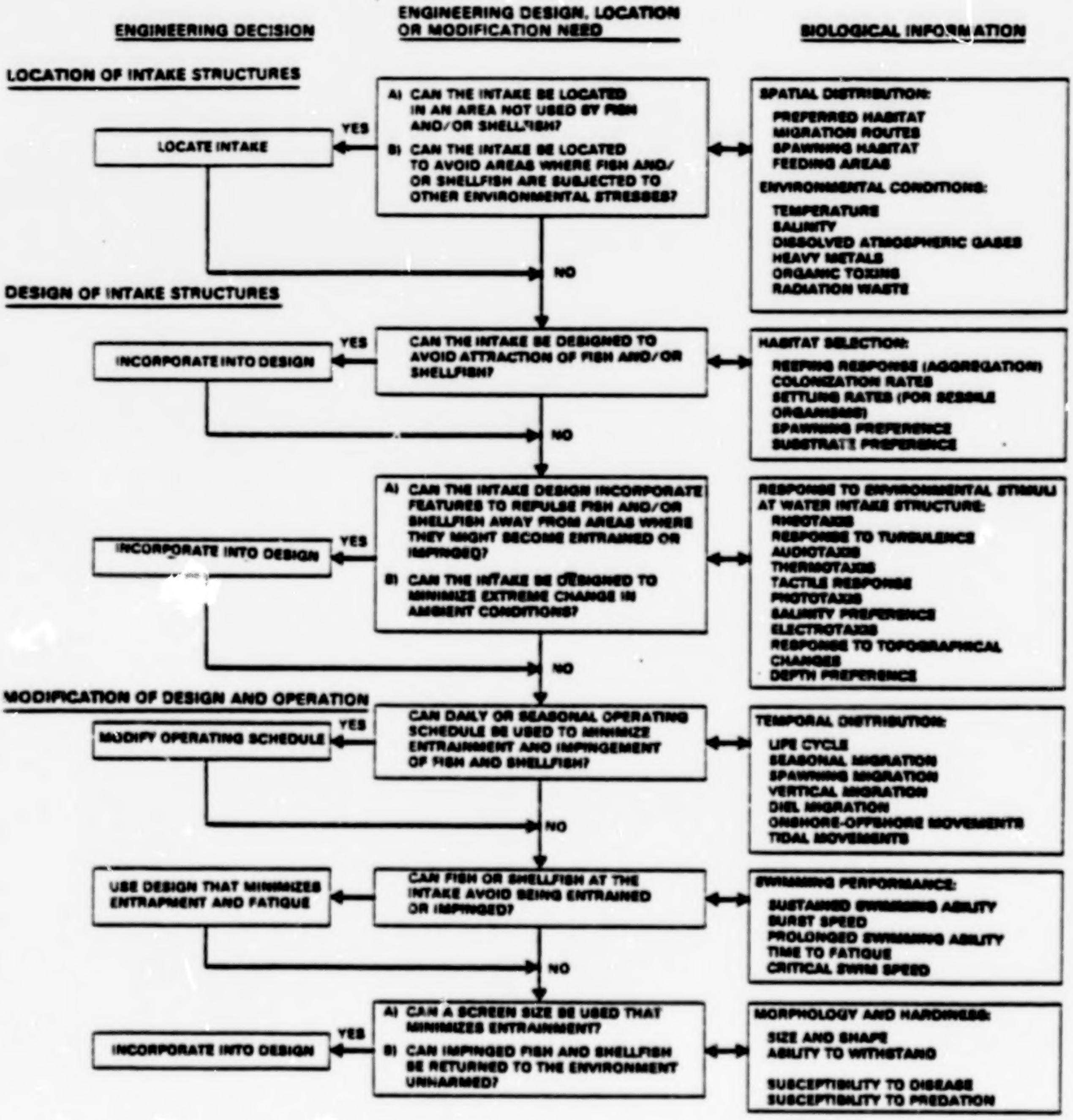
Figure 2. Biological and water intake characteristics that define stimulus/response relationships.

## Biological Characteristics

The behavioral, physiological, and ecological characteristics of fish and shellfish are complex and many are not applicable to intake design. However, by understanding those characteristics that influence vulnerability to entrainment and impingement, the biologist will have information that is pertinent to water intake structure design. The decision train in Figure 3 illustrates a method of sorting out pertinent information. Neitzel and McKenzie (1981) discuss the biological information in this decision train and present examples of how this information can be used in designing water intake structures. The following is a summary of the biological information presented in Neitzel and McKenzie (1981). The summary does not present all the biological information that is useful to water intake design; nevertheless, the examples should assist biologists in identifying the relationships between biological response of fish and shellfish and water intake designs that could lead to entrainment or impingement.

Distribution and habitat selection patterns are among the ecological characteristics that may be affected by water intake structures. When fish and shellfish spatial distributions occur near an intake, the likelihood of entrainment or impingement increases. Requirements for temperature, salinity, dissolved oxygen, food, and refuge from predators are among the factors a biologist should consider in looking at spatial distribution patterns. Because intake operations that occur when fish and shellfish are present increase fish and shellfish vulnerability to entrainment and impingement, temporal distribution patterns are also important. Some fish and shellfish move from one habitat to another (migrate) in response to environmental changes, food supplies and reproduction requirements. These migrations may occur seasonally, daily, or once in a lifetime. Fish and shellfish select habitats to hide or escape from predators, protect themselves from extreme changes in environmental conditions, or as suitable substrate for their particular environmental requirements. Shoreline configuration, substrate type, depth, and other topographical features of a body of water that are important in defining the habitat may be altered by the presence of an intake and thus merit consideration by a biologist.

Because species vary in their ability to withstand impact as well as in their response to intake stimuli, the biologist must consider species characteristics that might influence vulnerability. How indigenous fish and shellfish respond to stimuli such as bottom topography, current velocity, and sound may be important to intake design. If intake operation changes current direction or velocity, a biologist should be aware of those fish and shellfish that may be attracted to or entrained by these changes. Because the swimming performance of a fish near a water intake structure can be affected by current, velocity and direction patterns, the biologist should attempt to identify how currents at the intake will affect fish and shellfish. Consideration of fish and shellfish size and shape is important, since screen mesh sizes that allow fish and shellfish to pass through increase entrainment impacts. The ability of a fish or shellfish to withstand stresses varies with environmental



ENGINEERING DECISION
ENGINEERING DESIGN, LOCATION OR MODIFICATION NEED
BIOLOGICAL INFORMATION
LOCATION OF INTAKE STRUCTURES
A) CAN THE INTAKE BE LOCATED IN AN AREA NOT USED BY FISH AND/OR SHELLFISH?
B) CAN THE INTAKE BE LOCATED TO AVOID AREAS WHERE FISH AND/OR SHELLFISH ARE SUBJECTED TO OTHER ENVIRONMENTAL STRESSES?
YES
LOCATE INTAKE
SPATIAL DISTRIBUTION:
PREFERRED HABITAT
MIGRATION ROUTES
SPAWNING HABITAT
FEEDING AREAS
ENVIRONMENTAL CONDITIONS:
TEMPERATURE
SALINITY
DISSOLVED ATMOSPHERIC GASES
HEAVY METALS
ORGANIC TOXINS
RADIATION WASTE
NO
DESIGN OF INTAKE STRUCTURES
CAN THE INTAKE BE DESIGNED TO AVOID ATTRACTION OF FISH AND/OR SHELLFISH?
YES
INCORPORATE INTO DESIGN
HABITAT SELECTION:
REEFING RESPONSE (AGGREGATION)
COLONIZATION RATES
SETTLING RATES (FOR SESSILE ORGANISMS)
SPAWNING PREFERENCE
SUBSTRATE PREFERENCE
NO
A) CAN THE INTAKE DESIGN INCORPORATE FEATURES TO REPULSE FISH AND/OR SHELLFISH AWAY FROM AREAS WHERE THEY MIGHT BECOME ENTRAINED OR IMPINGED?
B) CAN THE INTAKE BE DESIGNED TO MINIMIZE EXTREME CHANGE IN AMBIENT CONDITIONS?
YES
INCORPORATE INTO DESIGN
RESPONSE TO ENVIRONMENTAL STIMULI AT WATER INTAKE STRUCTURE:
RHEOTAXIS
RESPONSE TO TURBULENCE
AUDIOTAXIS
THERMOTAXIS
TACTILE RESPONSE
PHOTOTAXIS
SALINITY PREFERENCE
ELECTROTAXIS
RESPONSE TO TOPOGRAPHICAL CHANGES
DEPTH PREFERENCE
NO
MODIFICATION OF DESIGN AND OPERATION
CAN DAILY OR SEASONAL OPERATING SCHEDULE BE USED TO MINIMIZE ENTRAINMENT AND IMPINGEMENT OF FISH AND SHELLFISH?
YES
MODIFY OPERATING SCHEDULE
TEMPORAL DISTRIBUTION:
LIFE CYCLE
SEASONAL MIGRATION
SPAWNING MIGRATION
VERTICAL MIGRATION
DIEL MIGRATION
ONSHORE-OFFSHORE MOVEMENTS
TIDAL MOVEMENTS
NO
CAN FISH OR SHELLFISH AT THE INTAKE AVOID BEING ENTRAINED OR IMPINGED?
USE DESIGN THAT MINIMIZES ENTRAPMENT AND FATIGUE
SWIMMING PERFORMANCE:
SUSTAINED SWIMMING ABILITY
BURST SPEED
PROLONGED SWIMMING ABILITY
TIME TO FATIGUE
CRITICAL SWIM SPEED
NO
A) CAN A SCREEN SIZE BE USED THAT MINIMIZES ENTRAINMENT?
B) CAN IMPINGED FISH AND SHELLFISH BE RETURNED TO THE ENVIRONMENT UNHARMED?
YES
INCORPORATE INTO DESIGN
MORPHOLOGY AND HARDINESS:
SIZE AND SHAPE
ABILITY TO WITHSTAND
SUSCEPTIBILITY TO DISEASE
SUSCEPTIBILITY TO PREDATION

Figure 3. Outline of biological information needed in designing, locating, or modifying of water intake structures.

conditions and health of the individual. Hardiness is important when considering modifications to water intake design such as fish removal systems.

The above examples are types of biological information that can be used in water intake structure designs. The next step in this first facet is to identify intake stimuli that influence biological responses of fish and shellfish.

## Water Intake Structure Stimuli

Water intake structures present stimuli that may elicit behavioral and physiological responses in fish and shellfish and change their vulnerability to entrainment and impingement. Water intake stimuli can also influence such ecological characteristics as distribution. An intake structure on a river shoreline, for example, usually has a forebay. A shore-oriented fish that approaches a forebay encounters a change in depth, light, and possibly temperature and bottom substrate. The fish may be attracted by the change in light intensity. If the fish is in an area that is near the intake screen, chances of impingement are increased.

When intake pumps are operating, the fish or shellfish approaching the intake encounters changes in water velocity, current direction and sound. Additionally, the intake design may include attractant and avoidance stimuli to reduce entrainment and impingement of aquatic organisms. Examples of water intake structure stimuli are discussed below. This summary does not present all the stimuli that may be present at a specific intake; it should, however, assist the biologist in identifying those stimuli that might affect fish and shellfish at a specific site.

When habitat changes resulting from the location of an intake attract fish and shellfish, these organisms may be more vulnerable to entrainment and impingement. The construction of a water intake structure results in the introduction of new habitat. It may serve as a new substrate for colonizing organisms. It can be a site for aggregating fish. Irregular surfaces on a water intake structure provide hiding places for small fish and shellfish and in turn, can create new forage areas for predator fish. The structure can also alter or affect water currents. Water intake designs can include intake channels, forebays, and dikes that are new habitat. Changes in habitat and how fish and shellfish respond to those changes must be considered in intake design.

Natural currents and sound or light patterns are changed by the presence of intake structures and may affect fish and shellfish in a variety of ways. Fish and shellfish may be attracted by currents at intakes. Ambient currents may change direction and velocity, and in turn affect swimming performance of fish and shellfish as well as the attractiveness of the altered area. If sounds caused by intake operations are perceived by fish and shellfish, the organisms may be attracted to areas where they will become impinged. Lights are found on many water intake structures for maintenance and security reasons. The shadows cast by intakes change sunlight patterns in the aquatic environment. Forebays, intake channels, and dikes at water intakes can result in changes in water depths that affect ambient light conditions.

These are the types of water intake stimuli that must be considered by a biologist who wants to define stimulus/response relationships for input to intake design. The next step in this facet of the process is defining water intake stimuli/biological response relationships.

## Stimulus/Response Relationships

The discussion of the first two steps of facet one provide examples of biological information and intake stimuli. As the third step, the biologist must articulate relationships between the intake stimuli and biological responses. As Figure 2 shows, this step involves a synthesis of the bodies of information discussed in the first two steps. The resulting information is selected to be useful to intake design.

We have already noted that the presence and operation of water intake structures present many stimuli that may elicit behavioral or physiological responses by fish and shellfish. The stimuli will vary with the intake design and the water body in which the intake is located. It is important to hypothesize the nature and magnitude of the stimuli that can then be related to biological responses of the indigenous fish and shellfish. These stimulus/response relationships can aid engineers in designing an intake that reduces attracting stimuli and increases repulsing stimuli (Table 2). The biologist using this procedure must determine which stimulus/response relationships are important. Following are examples of relationships that may affect the magnitude of entrainment and impingement.

Changes in current velocity or direction can attract fish and shellfish. If the current is near an intake screen and the velocity is at the threshold of endurance for an attracted fish, the fish may become impinged. If lights at a water intake structure are positioned so fish are attracted to areas where current velocities can impinge them, the stimulus (light)/response (attraction) increases impingement. The converse may result if lights attract fish away from impingement areas. Fish or shellfish may prefer certain shoreline configurations or depths. If an intake forebay or channel is excavated to depths preferred by vulnerable fish and shellfish, entrainment and impingement may be increased. Again, the converse holds true; an intake may be placed to avoid preferred depths of indigenous fish and shellfish. Operation of intake pumps and screen washing devices creates turbulence. If turbulence attracts fish or shellfish, entrainment and impingement will increase. Turbulence may affect fish or shellfish orientation and could affect an organism's response to other intake stimuli.

Table 2. Possible Stimulus/Response Relationships for Fish and Shellfish at Water Intake Structures and Potential Design Considerations to Reduce Entrainment and Impingement

| Intake Component | Stimuli | Reponse | Design Considerations |
|---|---|---|---|
| Structure | New habitat | Colonization | Surface modification unsuitable for colonization |
| | | Predator avoidance | Elimination from design area |
| | Change current | Attraction | Produce undetectable currents |
| Screens<br>Block Nets | Change current velocity and direction | Passage | Screen and mesh size that reduce passage |
| | | Attraction and fatigue | Decrease through-screen velocity |
| | Impingement | Injury or death | Safe removal system |
| Pumps | Noise | Attraction or repulsion | Use noise level that repulses |
| Skimmer or walls, bottoms, sills, porous dikes | Change currents | Attraction or repulsion | Produce currents that repulse fish |
| | Change access area | Blockage | Place in area that will prevent access |
| Discharge | Change temperature and current, chlorine | Change behavioral threshold | Place to avoid affecting population near intake |

These are only a few of the many relationships that can influence the vulnerability of fish and shellfish to entrainment and impingement. We suggest a method for sorting out those relationships that are relevant to a specific intake in Figure 4. Biological characteristics of indigenous fish and shellfish are listed on the left. Intake stimuli are listed on the top. The biologist who needs to provide meaningful information to intake design can use Figure 4 to identify and prioritize the relationships most likely to be pertinent to a specific intake.

Priorities will vary with intakes and indigenous fish and shellfish populations. Not all relationships may be useful. Some relationships may suggest modifications that are not economically feasible, or engineering design changes that are incompatible with the other facility components. Criteria for setting priorities are beyond the scope of this manual. However, before proceeding to facets 2 and 3 of the process, the biologist must prioritize stimulus/response relationships for the design engineer.

| INTAKE CHARACTERISTICS<br>SPECIES CHARACTERISTICS | CURRENT VELOCITY | TOPOGRAPHICAL CHANGES | DEPTH CHANGES | SHORELINE CONFIGURATIONS | LIGHT/SHADOWS | SOUND | STRUCTURE SHAPE | SCREEN MESH SIZE | WATER WITHDRAWAL LOCATION | CURRENT DIRECTION |
|---|---|---|---|---|---|---|---|---|---|---|
| RHEOTAXIS | | | | | | | | | | |
| PHOTOTAXIS | | | | | | | | | | |
| REEFING RESPONSE | | | | | | | | | | |
| AUDIOTAXIS | | | | | | | | | | |
| SWIM SPEED | | | | | | | | | | |
| TIME TO FATIGUE | | | | | | | | | | |
| ORGANISM SIZE | | | | | | | | | | |
| SWIMMING DEPTH | | | | | | | | | | |
| HABITAT PREFERENCE | | | | | | | | | | |

Figure 4. Decision matrix for identifying relevant stimulus/response relationships applicable to water intake structure design.

After the biologist defines relevant biological information (stimulus/response relationships that will reduce entrainment and impingement), the information has to be presented or communicated to design engineers in a useable form. We suggest that quantified descriptions of the stimulus/response relationships will provide an optimum common ground for communication between biologist and engineer. Methods for quantifying relationships are explored in a discussion of the next facet.

## QUANTITATIVE DESCRIPTIONS OF STIMULUS/RESPONSE RELATIONSHIPS

Once the stimulus/response relationships have been identified and analyzed, they must be communicated to the design engineer so they can be incorporated into the intake design. We suggest that a quantitative description of the stimulus/response relationship is the best way to communicate biological information to design engineers (Figure 5). The quantitative descriptions, besides communicating information, may suggest additional experiments for quantifying stimulus/response relationships, or they may direct the biologist to consider other stimulus/response relationships (Figure 5). In our discussion of facet 2, we present methods for quantifying relationships observed between water intake structure stimuli and biological responses of fish and shellfish populations.

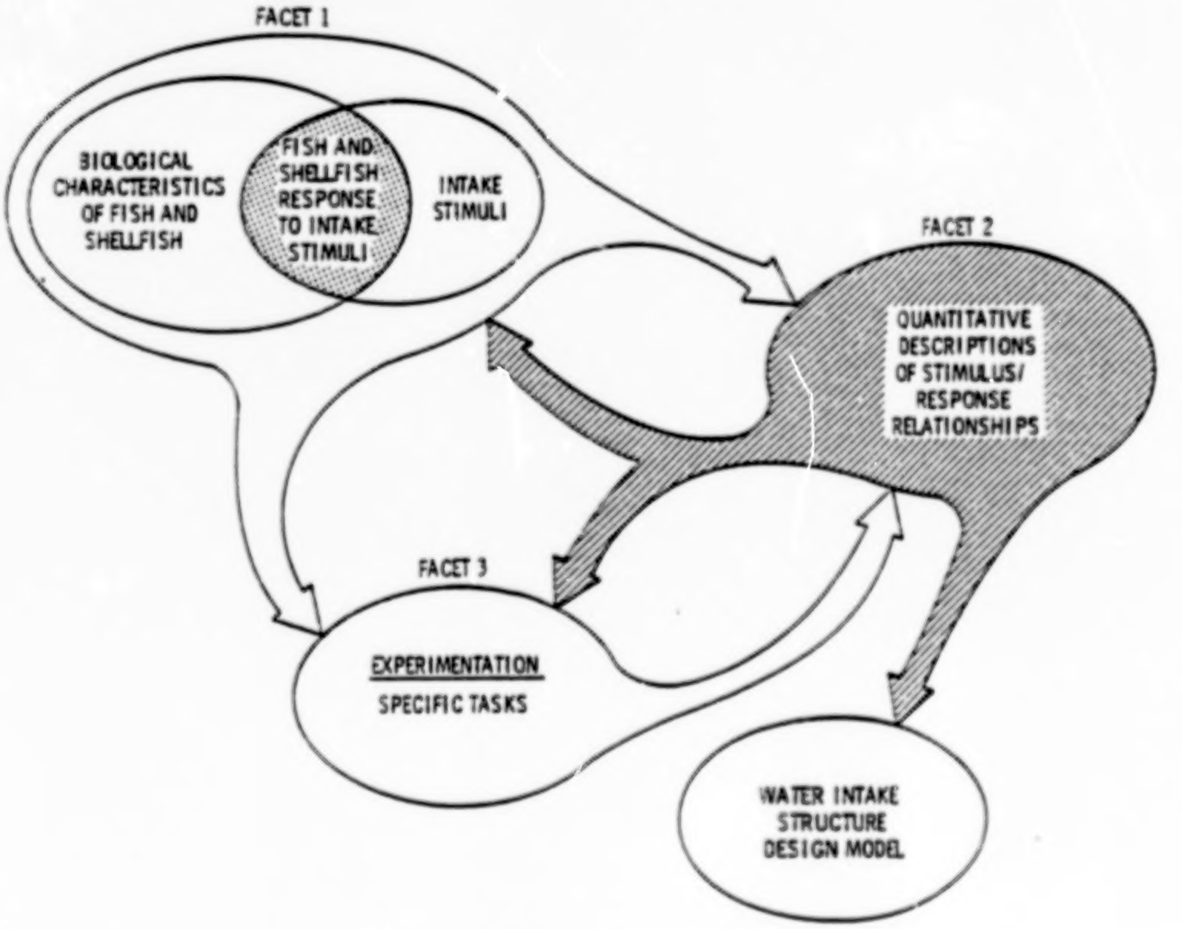

FACET 1
BIOLOGICAL CHARACTERISTICS OF FISH AND SHELLFISH
FISH AND SHELLFISH RESPONSE TO INTAKE STIMULI
INTAKE STIMULI
FACET 2
QUANTITATIVE DESCRIPTIONS OF STIMULUS/ RESPONSE RELATIONSHIPS
FACET 3
EXPERIMENTATION
SPECIFIC TASKS
WATER INTAKE STRUCTURE DESIGN MODEL

Figure 5. Relationship between quantitative stimulus/response data and other biological information needed to design, locate, or modify an intake.

## Functional Approach

Quantification of stimulus/response relationships is described in detail in Simmons and McKenzie (1981). Two methods of quantification are presented. In the first, functional relationships are developed between behavioral and physiological characteristics of fish and shellfish and changing environmental conditions that might affect vulnerability to entrainment and impingement. Examples include swim speed and preferences for temperature and salinity, etc. For this approach, models (mathematical equations) are developed to evaluate many stimulus/response relationships in concert. For example, a swim speed model might predict the effects of size (age), temperature, season and dissolved oxygen concentration on the swim speed of a particular fish species. These models require that biological responses be examined over a range of stimulus levels.

An example of this type of model is the swim speed model. The general form of the swim speed model is:

$$V = (aL^b) * f(T, SAL, DO, TOX, CF) \qquad (1)$$

where $V$ = swim speed (cm/sec)

$L$ = organism size (length)

$a,b$ = parameters

and $f(\ )$ = functions describing the effect of swim speed on:

T (temperature)

SAL (salinity)

DO (dissolved oxygen)

TOX (toxic compounds)

CF (some physiological factor e.g., sex, disease, schooling, etc.).

To construct such a model, functional relationships are needed between the biological characteristics and intake stimuli. These functions are derived from the experimental data via regression analysis, using either a best fit approach, or fitting postulated relationships. An example of the latter is the fish length/swim speed relationship, generally described by:

$$V = aL^b \qquad (2)$$

The relationship between temperature and swim speed can take a variety of forms. One common procedure is to use Equation 2 to describe the relationship between fish length and swim speed at each test temperature. The temperature/swim speed relation would then be composed of a series of equations, each having different parameter values. Another type of temperature/swim speed relationship can be derived from response surface analysis (Griffiths and Alderdice 1972).

For the swim speed model described in Simmons and McKenzie (1981), a multiplicative relationship was assumed between swim speed and the various physiological and environmental factors. Equation (1) then becomes:

$$V = (a * L^b) * f_1(T) * f_2(SAL) * f_3(DO) * f_4(TOX) * f_5(CF)$$

where $0<f_i(\cdot)<1$ for all i .

Functions for temperature, salinity, etc. are developed such that at preferred or optimum levels for these factors, swim speed is related only to fish size (e.g., $f_1(T) = 1$). At other than optimal conditions, the effect of temperature, salinity, etc., is a proportionate reduction of swim speed (e.g., $f_1(T) < 1$).

The relation between temperature and swim speed applicable to a multiplicative model is similar to that postulated for temperature and ingestion rates (Kitchell et al. 1974), where:

$$T = T_r^{\,t_x} * e^{t_x(1-T_r)}$$

where $T_r = (T_u - t) / (T_u - T_{opt})$

$$t_x = T_1^{\,2}[1+(1+40/T_2)^{0.5}]^2$$

$$T_1 = \ln T_Q(T_u - T_{opt})$$

$$T_2 = \ln T_Q * (T_u - T_{opt} + 2)$$

and $T_u$ = upper temperature limit at which swimming stops

$T_{opt}$ = preferred or optimum temperature

$T_Q$ = $Q_{10}$ (rate of change per 10 C) for swim speed

t = ambient or test temperature.

Functions describing the stimulus/response relationship need not be continuous. For example, the effect of disease on swim speed can be described by a discrete function:

$$CF = 1.0 \text{ if no disease,}$$

$$= V_{dis}/V_m \text{ if disease is present,}$$

where $V_{dis}$ = swim speed of diseased fish and

$V_m$ = maximum swim speed.

Development of functions is necessary for all the stimulus/response relationships identified as pertinent to describing swim speed. Since these functions are species- and in some cases size-specific, they will require multiple inputs for such parameters as preferred temperature ($T_{opt}$). Some of these functions and/or parameter values can be adapted from the literature.

Once the model is assembled, it can be used to compare the effect of the various stimuli on swim speed, and to predict swim speeds given a set of conditions. These predictions should be compared to actual swim speed data as a check when possible. Models such as the swim speed model are useful for planning experiments to examine the mechanisms and consequences of behavioral regulation or behavioral adaptations to environmental stimuli (Neill 1979). These models also provide input into the categorical approach.

## Categorical Approach

A second method of quantification involves assigning pertinent stimulus/response relationships to quantal categories. This approach emphasizes categories describing the spatial and temporal distribution of a species or life stage and makes maximum use of available or easily obtained information. In the decision process shown in Figure 3, a categorical approach is used to provide input into engineering questions on intake location and on modifications to intake design and operation.

The categorical approach satisfies most of the criteria for an optimal procedure that will provide biological input to an engineering design (Fritz et al. 1980). The categorical approach makes few critical assumptions about the state of nature and does not require large amounts of information. The mathematical model utilizing this approach can be easily programmed and used to evaluate multiple situations. Most of the information needed is easily obtained. The categorical approach, as presented here, evaluates intake design and location with a matrix model. Matrices provide an organizational framework that utilize the biological response and intake stimuli information organized in facet one. Categories within the biological response matrix (d) describe fish and shellfish distribution; categories in the intake stimuli vector (p) describe location and operating characteristics of the intake. The biological distribution matrix simply identifies whether a particular lifestage (rows) is present or absent in a given spatial or temporal category (columns). Elements of the vector (p) indicate whether or not the intake design is relevant to these same spatial and temporal categories. For example, if the intake operates during the day but not at night, then "1" would be entered in the row designating "day" and a "0" would be entered in the row designating "night". Multiplication of the two matrices yields information on the overlap in the zone of influence between the intake stimuli and the fish or shellfish response. Such an overlap signals potential for entrainment or impingement.

The general form of the matrix for fish and shellfish distribution ($\underline{D}$) is:

$$\underline{D} = \begin{vmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ d_{s1} & d_{s2} & \cdots & d_{sn} \end{vmatrix}$$

with $n$ = parameters associated with distribution

$s$ = life stages

and $d$ = response (0, 1).

Zero/one in the matrix signifies absence or presence, respectively. A separate matrix is constructed for each species considered at risk in the area of the intake. The rows of the matrix should include all potentially impacted life stages, while the distribution categories (columns) should include season (summer, fall, etc.), day/ night, in-shore/off-shore, or top/bottom. These categories are general; nevertheless, they describe the position of a fish or shellfish in time and space and are useful in a preliminary assessment of intake design. The categories become more specific as the assessment shifts from general location and design specifications to modifications of the intake structure.

Factors associated with the location of the water intake are contained in a vector ($\underline{P}$). In selecting factors, consideration is given to the extent of the area disturbed by the intake (e.g. by current), and, if the intake is located at the end of an intake canal, the characteristics of the canal (e.g. relative depth, where the intake water is drawn from). The intake vector is:

$$\underline{P} = \left| \begin{array}{c} p_{11} \\ p_{21} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ p_{n1} \end{array} \right|$$

where n = parameters associated with intake

and p = relevance to intake (0, 1) and the second 1 (n1) refers to the first design characteristic.

Overlap between a species distribution and the zone of influence around the intake are assessed as:

$$\text{Overlap} = \underline{1} * \underline{W} * (\underline{D} * \underline{P})$$

where $\underline{W}$ = s x s matrix of weights assigning importance to various life stages and

$\underline{1}$ = 1 x s vector of 1's.

The overlap variable is a scalar which measures the coincidence between the distribution of fish and shellfish and the spatial and temporal area occupied by the intake. The degree of overlap measures the potential for impact.

The procedure allows for a rapid assessment of many alternatives and provides a means of weighting these alternatives (matrix $\underline{W}$). In this example, the weights are assigned to the biological input. We assign higher weights to endangered species or to small size classes. Weights can also be based on the reproductive value of particular size classes. Weights related to the costs of the various intake designs and locations can also be added to the model. For example:

$$\text{Overlap} = \underline{1} * \underline{W} * (\underline{D} * \underline{E} * \underline{P})$$

where $\underline{E}$ = n x n diagonal matrix of economic weights.

This procedure provides an easy method for examining the effects of modifications to a proposed or in-place intake structure. Interacting with an engineer, the biologist can input ideas based on his own knowledge of the area as well as on corroborating evidence from other sites and studies.

Quantitative methodologies make the transfer of biological information to the design engineer easier in three ways. First, quantitative methodologies provide for an experimental design based on the statistical principles of randomization and replication. Such designs insure that hypotheses are both well-defined and testable. Second, models can be developed which describe the physiological and behavioral responses of an organism under conditions of many stimuli. This permits biologists and engineers to assess situations in which more than one intake stimuli (e.g. change in current direction and speed) affect the biological response of a fish or shellfish (e.g. swim speed). The third advantage comes from techniques for evaluating the potential impact of various intake designs and location options on indigenous fish and shellfish.

Quantification of stimulus/response relationships requires data. Though these data can be gleaned from reviews of available literature, information in journal articles and technical reports may not always be applicable to site-specific situations. Experiments that will generate useable data must be designed. To arrive at suitable experimental designs, questions about the exact nature of the relationships to be measured must be answered. Factors that could influence a relationship as well as the magnitude of the relationship must be considered. Input to the experimental design criteria also requires an assessment of acceptable error levels and a determination of sample size. A statistician should be consulted to insure that data collected will be appropriate for testing the desired hypothesis. Methods for defining specific tasks are presented in the following section.

## EXPERIMENTATION AND DATA ANALYSIS

Preceeding sections of this manual discuss the first and second facets of a process by which biological information may be incorporated into intake design considerations. The first facet includes: 1) identifying biological characteristics of fish and shellfish that influence the vulnerability of an organism to be entrained or impinged; 2) identifying water intake structure stimuli that elicit behavioral and physiological responses of fish and shellfish; and 3) describing stimulus/response relationships. The second facet describes quantification of the stimulus/response relationships (Figures 1, 2, and 5). Figure 6 highlights observation and collection of experimental data to support quantitative descriptions of water intake stimulus/organism response relationships. The organization which requires identification of stimulus/response relationships and quantification of these relationships can suggest experiments (Figure 6). Fritz et al. (1980) use a hierarchy of hypotheses for determining specific tasks to assess impacts of power plants on fish and shellfish populations.

A hierarchical process is used here to suggest specific tasks that will provide data appropriate to water intake design models (Figure 7). Primary, secondary, and tertiary hypotheses are usually too general to suggest specific tasks or experiments. However, lower order hypotheses are less general and can

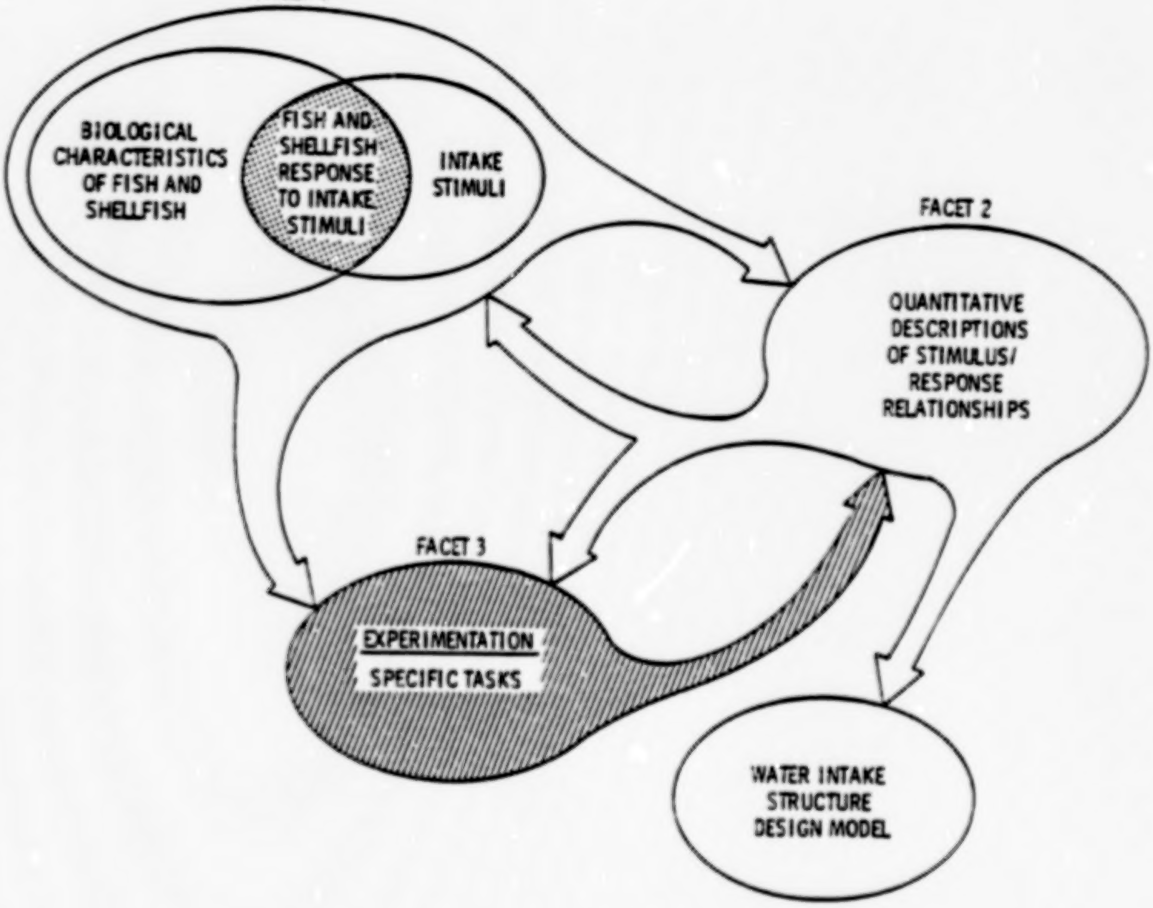

FACET 1
BIOLOGICAL CHARACTERISTICS OF FISH AND SHELLFISH
FISH AND SHELLFISH RESPONSE TO INTAKE STIMULI
INTAKE STIMULI
FACET 2
QUANTITATIVE DESCRIPTIONS OF STIMULUS/ RESPONSE RELATIONSHIPS
FACET 3
EXPERIMENTATION
SPECIFIC TASKS
WATER INTAKE STRUCTURE DESIGN MODEL

Figure 6. Specific tasks for quantifying descriptions of stimulus/response relationships.

suggest tasks that may generate data for parameterizing quantitative descriptions of stimulus/response relationships. Figure 8 is a hypothesis hierarchy diagram illustrating the relationship of fish swim speed (a physiological characteristic) to intake velocity (intake stimulus). Figure 9 repeats the hypothesis hierarchy, illustrating its applicability to an ecological characteristic (spatial distribution) of fish or shellfish which might be entrained or impinged at a water intake structure.

When first examining this hierarchical process, the examiner might easily become discouraged by the enormous number of tasks that can be generated. In Figure 7 (the generic hypothesis hierarchy), only three specific tasks are illustrated. However, if fully expanded to include all species of fish and shellfish, and all their behavioral, physiological, and ecological characteristics, plus all intake stimuli, the thousands of specific tasks defined would be of no help to a biologist providing input to water intake structure design. Therefore, a biologist using the hypothesis hierarchy has to use some form of

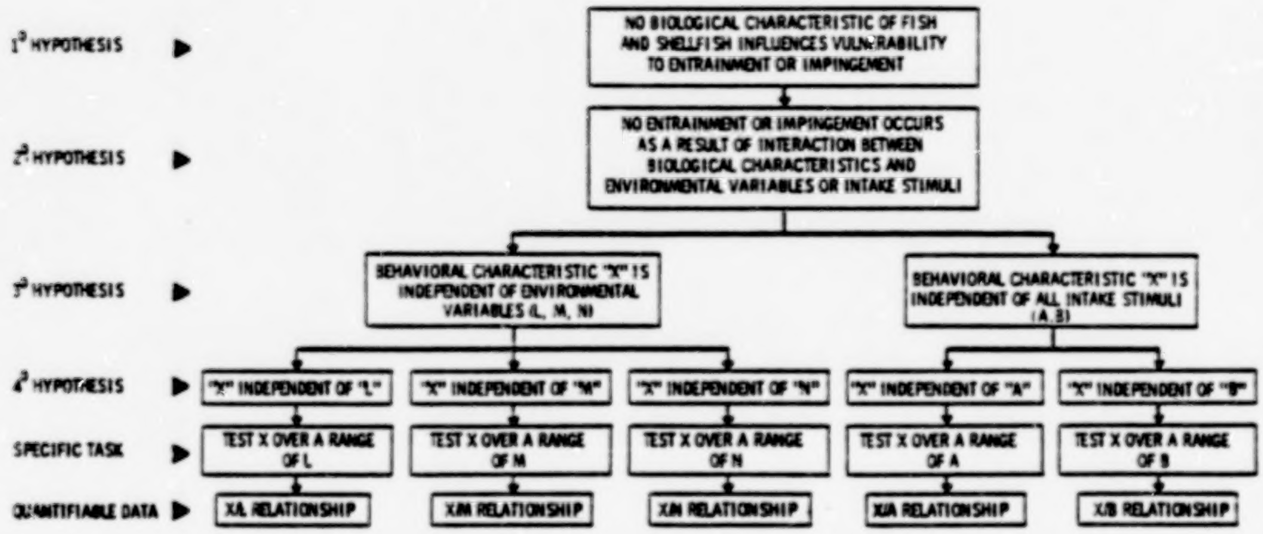

1° HYPOTHESIS
NO BIOLOGICAL CHARACTERISTIC OF FISH AND SHELLFISH INFLUENCES VULNERABILITY TO ENTRAINMENT OR IMPINGEMENT
2° HYPOTHESIS
NO ENTRAINMENT OR IMPINGEMENT OCCURS AS A RESULT OF INTERACTION BETWEEN BIOLOGICAL CHARACTERISTICS AND ENVIRONMENTAL VARIABLES OR INTAKE STIMULI
3° HYPOTHESIS
BEHAVIORAL CHARACTERISTIC "X" IS INDEPENDENT OF ENVIRONMENTAL VARIABLES (L, M, N)
BEHAVIORAL CHARACTERISTIC "X" IS INDEPENDENT OF ALL INTAKE STIMULI (A,B)
4° HYPOTHESIS
"X" INDEPENDENT OF "L"
"X" INDEPENDENT OF "M"
"X" INDEPENDENT OF "N"
"X" INDEPENDENT OF "A"
"X" INDEPENDENT OF "B"
SPECIFIC TASK
TEST X OVER A RANGE OF L
TEST X OVER A RANGE OF M
TEST X OVER A RANGE OF N
TEST X OVER A RANGE OF A
TEST X OVER A RANGE OF B
QUANTIFIABLE DATA
X/L RELATIONSHIP
X/M RELATIONSHIP
X/N RELATIONSHIP
X/A RELATIONSHIP
X/B RELATIONSHIP

Figure 7. A generic hypothesis hierarchy defining specific tasks for producing quantitative data on stimulus/response relationships.

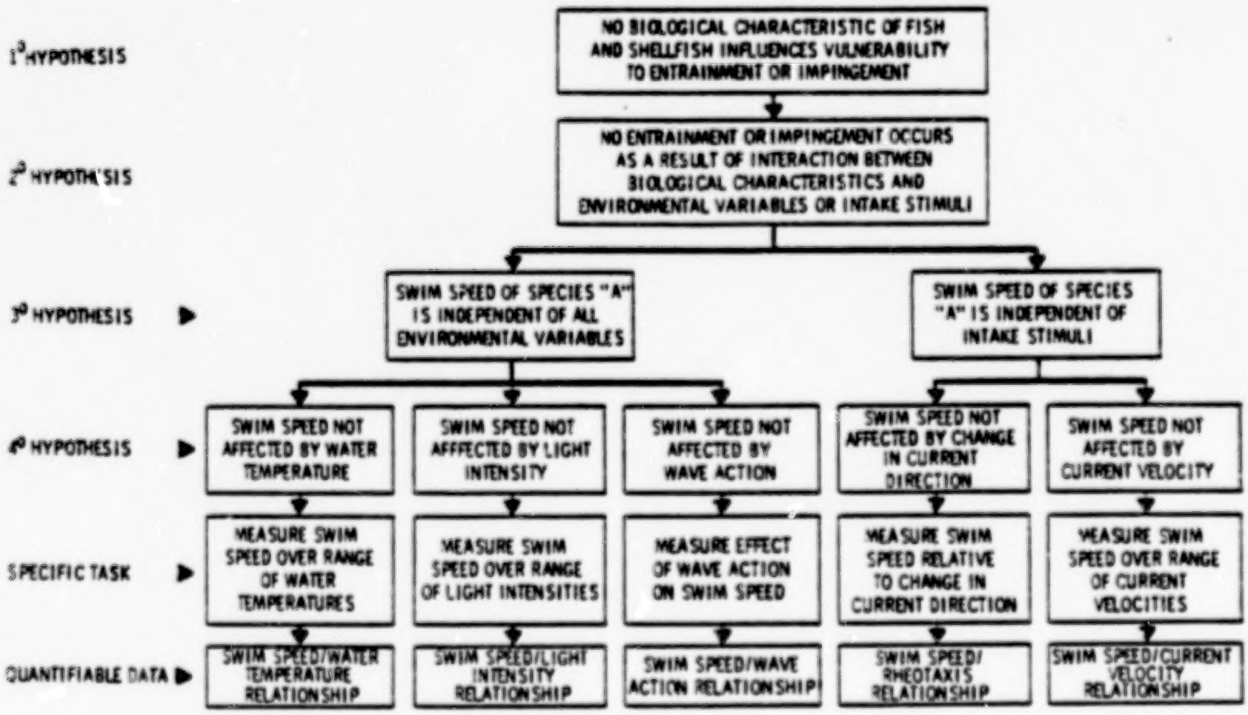

1° HYPOTHESIS
NO BIOLOGICAL CHARACTERISTIC OF FISH AND SHELLFISH INFLUENCES VULNERABILITY TO ENTRAINMENT OR IMPINGEMENT
2° HYPOTHESIS
NO ENTRAINMENT OR IMPINGEMENT OCCURS AS A RESULT OF INTERACTION BETWEEN BIOLOGICAL CHARACTERISTICS AND ENVIRONMENTAL VARIABLES OR INTAKE STIMULI
3° HYPOTHESIS
SWIM SPEED OF SPECIES "A" IS INDEPENDENT OF ALL ENVIRONMENTAL VARIABLES
SWIM SPEED OF SPECIES "A" IS INDEPENDENT OF INTAKE STIMULI
4° HYPOTHESIS
SWIM SPEED NOT AFFECTED BY WATER TEMPERATURE
SWIM SPEED NOT AFFFECTED BY LIGHT INTENSITY
SWIM SPEED NOT AFFECTED BY WAVE ACTION
SWIM SPEED NOT AFFECTED BY CHANGE IN CURRENT DIRECTION
SWIM SPEED NOT AFFECTED BY CURRENT VELOCITY
SPECIFIC TASK
MEASURE SWIM SPEED OVER RANGE OF WATER TEMPERATURES
MEASURE SWIM SPEED OVER RANGE OF LIGHT INTENSITIES
MEASURE EFFECT OF WAVE ACTION ON SWIM SPEED
MEASURE SWIM SPEED RELATIVE TO CHANGE IN CURRENT DIRECTION
MEASURE SWIM SPEED OVER RANGE OF CURRENT VELOCITIES
QUANTIFIABLE DATA
SWIM SPEED/WATER TEMPERATURE RELATIONSHIP
SWIM SPEED/LIGHT INTENSITY RELATIONSHIP
SWIM SPEED/WAVE ACTION RELATIONSHIP
SWIM SPEED/RHEOTAXIS RELATIONSHIP
SWIM SPEED/CURRENT VELOCITY RELATIONSHIP

Figure 8. A hypothesis hierarchy for quantifying swim speed/environmental stimulus relationships.

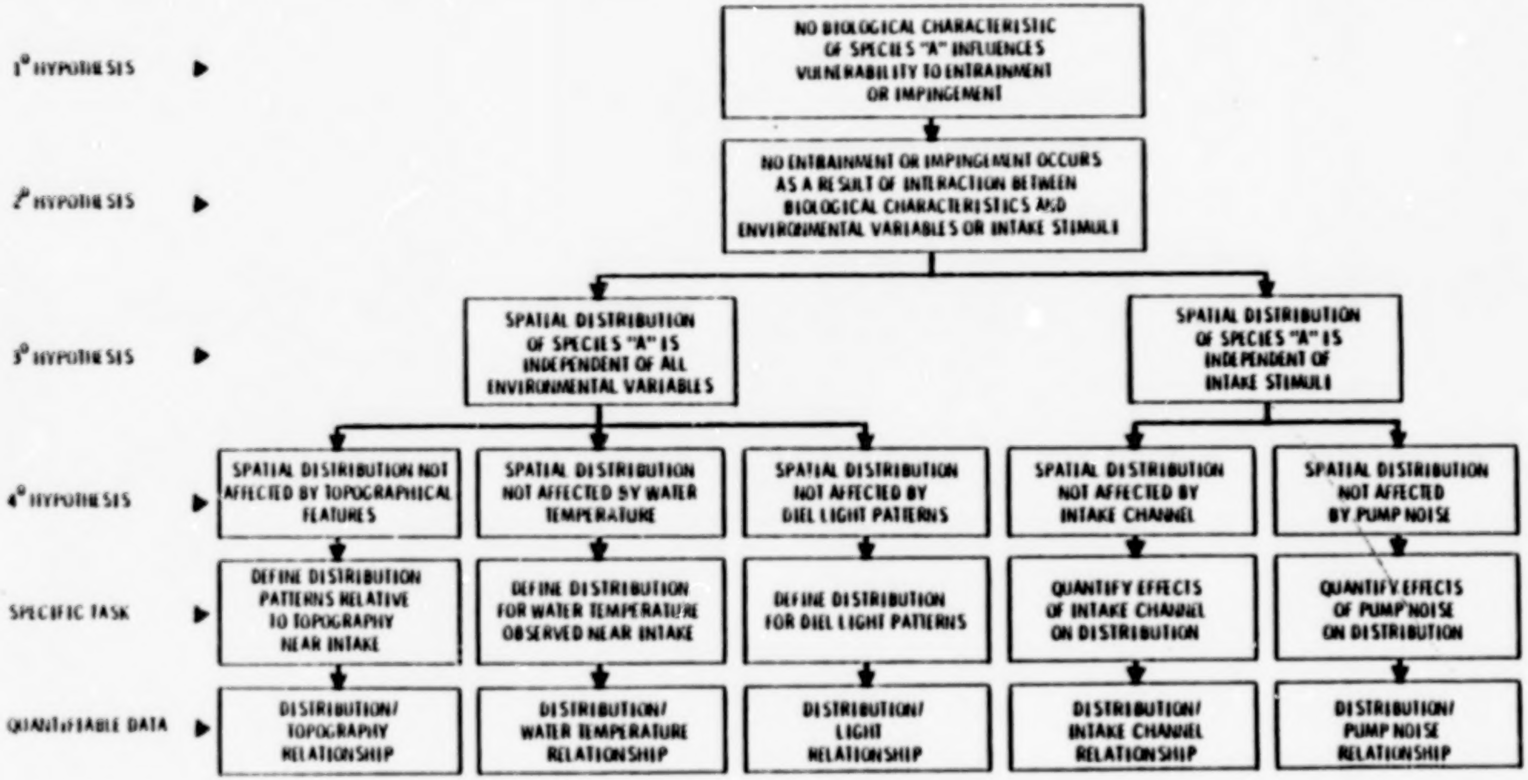

1° HYPOTHESIS
2° HYPOTHESIS
3° HYPOTHESIS
4° HYPOTHESIS
SPECIFIC TASK
QUANTIFIABLE DATA
NO BIOLOGICAL CHARACTERISTIC OF SPECIES "A" INFLUENCES VULNERABILITY TO ENTRAINMENT OR IMPINGEMENT
NO ENTRAINMENT OR IMPINGEMENT OCCURS AS A RESULT OF INTERACTION BETWEEN BIOLOGICAL CHARACTERISTICS AND ENVIRONMENTAL VARIABLES OR INTAKE STIMULI
SPATIAL DISTRIBUTION OF SPECIES "A" IS INDEPENDENT OF ALL ENVIRONMENTAL VARIABLES
SPATIAL DISTRIBUTION OF SPECIES "A" IS INDEPENDENT OF INTAKE STIMULI
SPATIAL DISTRIBUTION NOT AFFECTED BY TOPOGRAPHICAL FEATURES
SPATIAL DISTRIBUTION NOT AFFECTED BY WATER TEMPERATURE
SPATIAL DISTRIBUTION NOT AFFECTED BY DIEL LIGHT PATTERNS
SPATIAL DISTRIBUTION NOT AFFECTED BY INTAKE CHANNEL
SPATIAL DISTRIBUTION NOT AFFECTED BY PUMP NOISE
DEFINE DISTRIBUTION PATTERNS RELATIVE TO TOPOGRAPHY NEAR INTAKE
DEFINE DISTRIBUTION FOR WATER TEMPERATURE OBSERVED NEAR INTAKE
DEFINE DISTRIBUTION FOR DIEL LIGHT PATTERNS
QUANTIFY EFFECTS OF INTAKE CHANNEL ON DISTRIBUTION
QUANTIFY EFFECTS OF PUMP NOISE ON DISTRIBUTION
DISTRIBUTION/ TOPOGRAPHY RELATIONSHIP
DISTRIBUTION/ WATER TEMPERATURE RELATIONSHIP
DISTRIBUTION/ LIGHT RELATIONSHIP
DISTRIBUTION/ INTAKE CHANNEL RELATIONSHIP
DISTRIBUTION/ PUMP NOISE RELATIONSHIP

Figure 9. A hypothesis hierarchy to quantify spatial distribution/intake location relationships.

a decision train (e.g. Figure 3) to select those species and biological characteristics that are most applicable to site-specific design under consideration. The biologist should also rely on information generated by quantitative descriptions of stimulus/response relationships (Figure 5) when selecting specific tasks that will generate appropriate data.

# SITE-SPECIFIC EXAMPLES

Water intake structures associated with two power plants are used to illustrate the procedures outlined in this manual. In the first example, an entrainment and impingement problem was mitigated by incorporating biological information into design modifications. In the second example, impingement data from a power plant is used to illustrate the quantitative procedure.

The first example involves a water intake structure associated with the Hanford Generating Project (HGP) located on the Columbia River in southeastern Washington (Gray et al. 1979). Here, protection of migrating salmon populations was the primary biological concern. Water intake structures, especially those located near spawning areas, have the potential for impinging and entraining salmon fry.

Salmon fry were found to be both impinged and entrained at HGP (Gray et al. 1979). The procedure used to mitigate the impact was similar to the one proposed in this manual. First, the characteristics of the biological community were determined (in this case the salmon population); the characteristics of the intake which might contribute to the problem were analyzed as well. Biological and ecological characteristics of the salmon fry collected in the vicinity of the intake, and of those collected in front of and behind the traveling screens were listed (Table 3). Also in Table 3 are intake stimuli which were thought to affect impingement and entrainment. The impacted population consisted of fry (3.5 to 6.5 cm) which were present for a four month period in spring. Several characteristics of the intake appeared to be related to the impingement and entrainment problem. These included a large mesh on the intake screens, an intake velocity which greatly exceeded the swim speed of salmon fry, and the withdrawal of water from the frys' preferred habitat. These three areas were then targeted for possible design modifications (Figure 10).

The most obvious design modification, reduction of intake velocity, was not economically or operationally feasible. The other design options involved changing the depth from which the water was withdrawn and modifying the traveling screen. Since entrainment resulted in 100% mortality of salmon fry, modifications to reduce entrainment were considered first. The size structure of the entrained population (Table 3) indicated that entrained slamon exceeded the intake mesh size. Thus, while some fish might be passing through the screen, other means of access must also be possible. Physical examination of the screen revealed several areas which would allow passage of fish. The solution to the entrainment problem was to change the mesh size from 0.64 to 0.32 cm, and to close all gaps in and around the traveling screen.

Completion of these modifications effectively reduced the entrainment problem at HGP, but increased the impingement problem. With fewer salmon going through the screen, more were impinged; also, the smaller mesh size may have increased the velocity through the screen around the intake.

Table 3. Characteristics of the Salmon Fry Community (A) and Water Intake Structure (B) at the Hanford Generating Project (HGP) on the Columbia River, Washington (Gray et al. 1975)

A. Salmon Fry

1. Size Classes: cm (X: present, - : absent)

| | | Important Months | | | |
|---|---|---|---|---|---|
| | | Mar | Apr | May | June |
| a. | Beach Seine | | | | |
| | 3.5 - <6.5 | X | X | X | X |
| | 6.5 - <16.0 | X | X | X | X |
| | 16.0+ | X | - | - | - |
| b. | Impinged | | | | |
| | 3.5 - <6.5 | X | X | X | X |
| | 6.5 - <16.0 | - | - | X | X |
| | 16.0+ | - | - | - | - |
| c. | Entrained | | | | |
| | 3.5 - <6.5 | X | X | X | X |
| | 6.5 - <16.0 | - | - | - | X |
| | 16.0+ | - | - | - | - |

2. Salmon fry migrate in upper 2 meters along shore

3. Prolonged swim speed for O. tschawytscha (Chinook Salmon) fry (3-10 cm) ranges from 40-70 cm/sec (Beamish 1978).

B. Intake
1. Mesh size of traveling screen: 0.64 cm
2. Water withdrawn from inshore area
3. Intake velocity: 72 cm/sec (approx.)

Examination of the salmon fry habitat (Table 3) indicated two possible solutions to reducing impingement. One was to modify the water intake to withdraw water from the bottom of the water column instead of the top. The other involved furth. modifications to the traveling screen.

At this stage, hypotheses were formulated about the effect of water withdrawal on impingement and the effect of screen modification on impingement mortality. These hypotheses were ranked according to their probability of success, i.e., the information resulting in a significant reduction in impingement or impingement mortality, and on economic considerations related to the

| INTAKE CHARACTERISTICS / SPECIES CHARACTERISTICS | CURRENT VELOCITY | TOPOGRAPHICAL CHANGES | DEPTH CHANGES | SHORELINE CONFIGURATIONS | LIGHT/SHADOWS | SOUND | STRUCTURE SHAPE | SCREEN MESH SIZE | WATER WITHDRAWAL LOCATION | CURRENT DIRECTION |
|---|---|---|---|---|---|---|---|---|---|---|
| RHEOTAXIS | | | | | | | | | | |
| PHOTOTAXIS | | | | | | | | | | |
| REEFING RESPONSE | | | | | | | | | | |
| AUDIOTAXIS | | | | | | | | | | |
| SWIM SPEED | ● | | | | | | | | | |
| TIME TO FATIGUE | | | | | | | | | | |
| ORGANISM SIZE | | | | | | | | ● | | |
| SWIMMING DEPTH | | | | | | | | | | |
| HABITAT PREFERENCE | | | | | | | | | ● | |

Figure 10. Decision matrix for identifying relevant stimulus/response relationships for the HGP water intake structure.

cost of the experiment and the cost of implementing the indicated modification. At HGP, the effect of the water withdrawal location was evaluated first. Stoplogs (adjustable concrete walls) at the intake were raised and lowered, restricting the area of water withdrawal. Results indicated no significant effect on impingement (Gray et al. 1979).

Hypotheses related to traveling screen modification were formulated for further study. The studies included: 1) feasibility of catching fry in shallow buckets welded to the traveling screens, 2) tolerance of fry to short term capture in the buckets on continuously traveling screens, and 3) survival of fry washed from the buckets and returned to the river downstream of the intake. Results of the tests indicated almost complete elimination of chinook salmon fry impingement mortalities at HGP.

The process for ameliorating the impingement and entrainment problem at HGP was to 1) identify the biological characteristics of the impacted population, 2) identify the characteristics of the intake which might affect impingement and entrainment, 3) evaluate selected stimulus/response relationships and

4) implement modifications based on the results of these evaluations. This procedure resulted in the elimination of salmon fry entrainment and a significant reduction in impingement mortality. Results from this investigation also suggested a design for future intake structures which might further reduce impingement (Gray et al. 1979).

The second example illustrates the quantitative procedure utilizing the categorical approach. The water intake structure for the Peach Bottom Atomic Power Station is located on an impoundment on the Susquehanna River, Pennsylvania (Mathur et al. 1977). A study of impingement rates at Peach Bottom indicated no significant impact existed (Mathur et al. 1977); results from that study are used here for illustrative purposes only.

If we were to design a study to reduce impingement at Peach Botton, we would first compile a list of those characteristics of the biological community considered important. At Peach Bottom, impingement of game fishes is an important priority; thus, we would consider such species as: Micropterus dolomieui (smallmouth bass), M. salmoides (largemouth bass), Stizostedion vitreum (walleye), Esox masquinongy (muskellunge), and Pomoxis annularis (white crappie) at this site.

Biological characteristics of these species that might affect impingement rates include fish size, swim speed, temporal distribution, and diel distribution.

The next step would be to consider the characteristics of the intake site and operation which also might affect impingement rates. Those characteristics shown to be important at Peach Bottom were pumping capacity (i.e., intake velocity), river flow (i.e., current), and water temperature (Mathur et al. 1977). These biological and intake characteristics now identify several areas for evaluation (Figure 11).

To illustrate the categorical approach, we evaluated the effect of temperature on the relationship between intake velocity and swim speed for Micropterus dolomieui, smallmouth bass. M. dolomieui is a seasonal migrator, moving from inshore areas in the fall to deeper offshore waters in winter, and returning to inshore areas in spring (Scott and Crossman 1973). Information on swim speed as a function of temperature was also available (Table 4).

Given some hypothetical information on average seasonal water temperatures at Peach Bottom (e.g., spring: 15°C; summer: 25°C; fall: 15°C; winter: 10°C), we can translate the swim speed data into a matrix (D) indicating the relationship of M. dolomieui to the intake (Table 5). The information for intake velocity and swim speed by season was derived as follows: an average winter temperature of 10°C was taken to correspond to an acclimation temperature of 10°C. The highest swim speed attained by M. dolomieui at 10°C acclimation temperature was <20 cm/sec. Thus, an intake velocity of 15 cm/sec would be below the swim speed of the fish (=0), while an intake velocity of 25 cm/sec would exceed the swim speed of the fish in winter (=1). The same logic was used to fill in the remainder of the matrix.

| SPECIES CHARACTERISTICS \ INTAKE CHARACTERISTICS | CURRENT VELOCITY | TOPOGRAPHICAL CHANGES | DEPTH CHANGES | SHORELINE CONFIGURATIONS | LIGHT/SHADOWS | SOUND | STRUCTURE SHAPE | SCREEN MESH SIZE | WATER WITHDRAWAL LOCATION | CURRENT DIRECTION |
|---|---|---|---|---|---|---|---|---|---|---|
| RHEOTAXIS | | | | | | | | | | |
| PHOTOTAXIS | | | | | | | | | | |
| REEFING RESPONSE | | | | | | | | | | |
| AUDIOTAXIS | | | | | | | | | | |
| SWIM SPEED | ● | | ● | | | | | | | |
| TIME TO FATIGUE | | | | | | | | | | |
| ORGANISM SIZE | ● | | ● | | | | | | | |
| SWIMMING DEPTH | | | | | | | | | | |
| HABITAT PREFERENCE | | | | | | | | | | |

Figure 11. Decision matrix for identifying relevant stimulus/response relationships applicable to the Peach Bottom water intake structure.

Table 4. Swim Speed as a Function of Temperature at Peach Bottom (Larimore and Duever 1968)

| Swim Speed (cm/sec) | Acclimation Temperature (°C) 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|
| <15 | X(a) | X | X | X | - |
| 15 - <20 | X | X | X | X | X |
| 20 - <25 | -(b) | X | X | X | X |
| 25 - 30 | - | - | X | X | X |
| 30+ | - | - | - | - | X |

(a) X: swim speed attained
(b) -: swim speed not attained.

Table 5. Matrix Showing Relationship of M. dolomieui to Intake at Peach Bottom

| M. dolomieui | Distribution | | Intake Velocity (cm/sec) | |
|---|---|---|---|---|
| | inshore | offshore | 15 | 25 |
| winter | 0 | 1 | 0 | 1 |
| spring | 1 | 0 | 0 | 1 |
| summer | 1 | 0 | 0 | 0 |
| fall | 0 | 1 | 0 | 1 |

Matrices for two possible intake designs were constructed (P):

| | Design A | Design B |
|---|---|---|
| inshore | 1 | 1 |
| offshore | 0 | 0 |
| intake velocity 15 | 1 | 0 |
| (cm/sec) 25 | 0 | 1 |

(0 = absent; 1 = present)

Both designs A and B have their intakes located inshore; the intake velocity for design A is 15 cm/sec and 25 cm/sec for design B.

We next constructed a weight matrix. Out of a range of 1 to 5, we assigned 4 to the spring population of M. dolomieui, since that represents the reproducing population. The summer population was given a 3, and fall and winter were both assigned a 2. This assignment was arbitrary; it would be based on the biologist's knowledge of the aquatic community and an understanding of important community members. The resulting weight matrix (W) for this example is:

$$\begin{array}{lcccc}
\text{winter} & 2 & 0 & 0 & 0 \\
\text{spring} & 0 & 4 & 0 & 0 \\
\text{summer} & 0 & 0 & 3 & 0 \\
\text{fall} & 0 & 0 & 0 & 2
\end{array}$$

We can now evaluate the potential effect of intake designs A and B on *M. dolomieui*. The vectors resulting from the matrix multiplication $\underline{W} * (\underline{D} * \underline{P})$ are:

| | Design A | Design B |
|---|---|---|
| winter | 0 | 2 |
| spring | 4 | 8 |
| summer | 3 | 3 |
| fall | 0 | 2 |

The overlap index is 7 for design A and 15 for B; however, ratio comparisons are not applicable. Design B is not 2.14 times as bad as design A (15/7). Rather, design A is simply ranked over design B.

These results suggest a higher impingement of *M. dolomieui* in the spring, and this would affect the reproducing population. Also, design A should have a smaller relative effect than design B. Further analysis could consider the relationship between fish size and impingement, or the effect of river flow and pumping operation on fish impingement. These last two factors were found to be positively correlated to impingement rates at Peach Bottom (Mathur et al. 1977). Stimulus/response relationships which could be related to pumping operation include current velocity/swim speed, turbulence/rheotaxis/organism size, and current direction/rheotaxis. High river flows could affect rheotaxic behavior and habitat preference. Results from these studies could indicate what design modifications would reduce impingement at Peach Bottom.

## FUTURE RESEARCH

Information compiled in this manual and the techniques suggested can be used to provide the most useful biological input to the design, location, or modification of water intake structures. Current research needs and possible experimental solutions are outlined in Table 6.

Table 6. Research Needs and Recommended Experimental Solutions

| Research Needs | Recommended Experimental Solution |
|---|---|
| • Definition and quantification of multiple stimulus/response relationships for fish and shellfish | • Integration of the effect of these stimuli on fish swim performance, relative to intake velocities, will help to predict the probability of impingement over a range of velocities. |
| • Behavioral, physiological, and ecological investigations specific to water intake structure stimuli | • Studies of the reefing response of fish to new structures have aimed to enhance sport and commercial catches. The possibility of incorporating reefing response behavior into intake designs to reduce entrainment and impingement warrants investigation. |
| • Threshold response to specific stimuli | • Rheotaxic responses are known for many fish species. Such information should be useful in designing intakes if engineers know the range at which current velocities are detected by fish. |
| • Environmental preference relative to intake stimuli and physiological limitations | • The relationship between oxygen consumption of fish and laboratory-measured swim speed is not linear. Hanson and Li (1978) examined this relationship and predicted an optimal swim speed that may be more useful in defining intake velocities that fish can avoid. |
| • Change in probability of entrainment and impingement with ontological differences for fish and shellfish | • Young fish and shellfish are usually more vulnerable to changes in environmental conditions, and biological information for one life stage may not be applicable to others. Therefore, age or life stage specific information is required for designing water intake structures. |

## MULTIPLE STIMULUS/RESPONSE RELATIONSHIPS

As suggested by field observations of fish impingement, more than one environmental or water intake stimulus affects the vulnerability of individuals to impingement or entrainment. Dorn et al. (1979) studied the swimming performance of nine species of common California inshore fish. The objective of the study was to determine the swimming abilities of fish species entrapped by offshore water intakes. Sustained, burst, and prolonged swimming performance were measured or calculated. Dorn et al.'s (1979) data and analysis suggest that for the species tested, even the smallest fish are capable of escaping by burst swimming. Dorn et al. (1979) state that intake velocities should not be a major consideration in evaluating causative factors of fish entrapment. They suggest that additional ambient environmental factors such as wave action, light and fish schooling and feeding behavior may influence entrainment and impingement of the fish studied.

Figure 12 suggests a graphic representation of Dorn et al.'s (1979) observations and what they might suggest for studying multiple stimulus/response relationships. Illustrated here is what occurs when behavior and physiology of individuals is affected by wave action, temperature, light or other environmental factors. All the environmental stimuli that affect swim speed cannot be simulated in a laboratory study. Cost-effective techniques for field measurements of fish swim speed are not available. Although radio telemetry can be used to evaluate swim speeds in the field, these studies are expensive and are not applicable to studies of smaller forage fish. This is probably one of the most important areas of research that warrants investigation before biologists can provide truly useful input to the design, location, or modification of water intake structures.

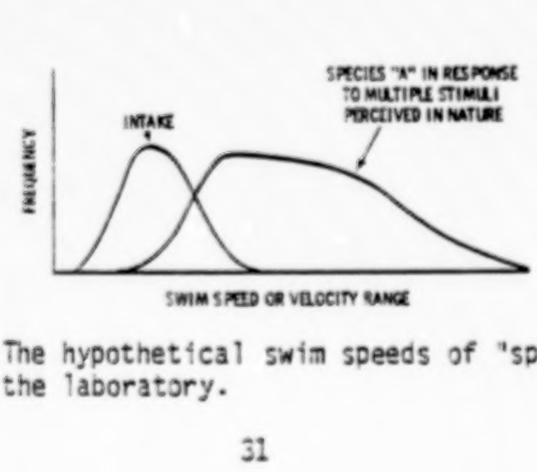


Figure 12. The hypothetical swim speeds of "species A" as measured in the laboratory.

## RELATIONSHIPS SPECIFIC TO INTAKE STIMULI

Water intake structures present new or altered habitat in the aquatic environment. With the beginning of construction, the natural or present habitat is changed and the water intake structure provides an area for colonization and aggregation of aquatic species. The structure, after construction, may also act as a stimulus that attracts or repulses fish and shellfish. Intake structures may vary in their component parts (e.g., intake channel and shoreline interface). The water body in which an intake is located will also in part determine the stimuli that are received by fish and shellfish. Four major types of water bodies in which intake structures are located are rivers, lakes and reservoirs, estuaries, and oceans (Sonnichsen et al. 1975). Table 7 shows some

Table 7. Physical Characteristics and Biological Considerations for Location of Water Intake Structures in Four Water Body Types, (in part from Sonnichsen 1975)

| Water Body | Physical Characteristics | Biological Considerations |
|---|---|---|
| Rivers | uni-directional flow that usually prevents recirculation; therefore, shoreline location. | habitat usually used by juvenile life stages. |
| | forebay necessary for lowest expected flow. | change in shoreline topography. |
| | operation procedures for ice and debris removal | ice and debris accumulation may make attractive habitat. |
| | | removal operation may result in environment stress (e.g., thermal shock). |
| | structure can cause eddies | juvenile unable to control swimming in eddies. |
| | | eddy provides concentration of food organisms. |
| Lakes and Reservoirs | temperature stratification | withdrawn water temperature may be preferred by fish. |
| | | discharge can alter stratification. |
| | offshore structures used | new habitat. |
| | recirculation (especially lakes) | biocides may be discharged near intake. |
| Estuaries | flow reversal | same consideration as recirculation in lakes. |
| | stratification | similar to lakes. Salinity, which is important to distribution of estuarine populations, may be affected. |
| | location | commonly used as spawning and nursery area for many marine species. |
| Oceans | surf and waves often require offshore location | must know migratory patterns in proposed locations. |
| | salinity | may affect composition of marine communities. |
| | flow changes with tides | affects communities as discharge changes. |

of the physical differences and how these differences might affect biological information needed for design considerations. Knowing how fish and shellfish will respond to the physical presence of an intake is important. If the design can include features that repulse or do not attract fish and shellfish, entrainment and impingement may be decreased.

## THRESHOLD RESPONSE

An important concept to consider when evaluating intake stimulus/organism response relationships is the threshold of an organism's response to a stimulus. If the intake is providing a stimulus at the threshold of an organism's ability to respond, response may occur after the fish is no longer able to avoid entrainment or impingement. Fish may avoid certain current velocities; however, if these velocities are too near the screens of an intake, the fish becomes impinged. The threshold of detection and the threshold of response capability have to be understood to predict the entrainment or impingement of a fish or shellfish.

A similar behavioral response might be acclimation to a stimulus. Often the strength of response is directly related to the degree of change in the stimulus. An intake design could include this type of information if the above relationship were known. For example, if a fish responds negatively to turbulence (swims away), turbulence might be used to direct fish away from areas where they might become entrained or impinged. However, if the turbulence is not enough to elicit immediate response, the fish may acclimate to the turbulence and continue to swim toward the intake.

## ENVIRONMENTAL PREFERENCE

Hanson and Li (1978) provide a useful example of the relationship between environmental preference of a fish species and how this might relate to the probability of entrainment or impingement. They present research results for chinook salmon, bluegill, and Mississippi silversides, relating oxygen consumption and swim speed. Their data show the selected current velocity for these species and reveal a better relationship between the optimum swimming speeds of these fish and impingement velocities than between impingement velocities and fish swim stamina. These results indicate a need for experimental correlation between behavioral and physiological characteristics as they apply to water intake design criteria.

## ONTOLOGICAL CONSIDERATIONS

Among the many variables that can affect the organism's response to a given environmental stimulus, one of the more important is the organism's age or stage of development. Young fish and shellfish are usually more vulnerable to changes in environmental conditions, and biological information for one life stage may not be applicable to others. Therefore, age or life stage specific information is required for designing water intake structures. If mathematical descriptions of biological information are developed, ontological changes should be included. For example, changes from planktonic to nektonic modes can influence the potential for entrainment and impingement of many fish and shellfish species. In most instances, different life stages may be considered as different organisms.

The feeding habits of fish change as they develop from larva to adult. Freshwater drum young eat zooplankton and chironomids mostly, while adults eat insects, fish and crayfish (Scott and Crossman 1973). Morsell and Norden (1968) noted that landlocked adult alewives eat zooplankton until they are about 119 mm long, and larger fish eat increased numbers of benthic amphipods. The diet of striped bass changes from zooplankton to small fishes throughout life. Thus, feeding habits of many young fish could influence their susceptibility to entrainment and impingement.

Changing size can affect the way in which an organism responds to a stimulus. Beamish (1978) discusses many investigations of swimming performance related to fish length and weight. Atlantic herring swimming endurance increases as body length increases. The distance a sea lamprey can swim in laboratory tests increases with their weight. The burst swimming speed for brown trout, Atlantic herring and goldfish was observed to decrease relative to increasing length. This type of physiological information is important for the design, operation or modification of a water intake structure at which current velocities are expected to affect fish swim performance. To choose a location, a screen size or approach velocity, the design engineer must know how the relevant biological information changes with ontological differences in fish and shellfish.

# CONCLUSIONS

The strategy outlined here is a guideline for providing biological input to the design, location or modification of a water intake structure. The process has three facets and is iterative, because information obtained in one facet of the process may be used to modify information needs.

The first facet requires a review of behavioral, physiological and ecological characteristics of fish and shellfish. The relationships between water intake stimuli and behavioral and physiological responses of fish and shellfish are evaluated. The biological information that is most likely to reduce entrainment and impingement is selected for inclusion in the water intake design. The second facet of the process describes methods for quantifying descriptions of stimulus/response relationships. Quantitative descriptions are used to aid communication between biologists and design engineers. The third facet identifies procedures for using information developed in facets 1 and 2 to support or further develop biological information relevant to intake designs. A hypothesis hierarchy is presented that aids identification of specific tasks for generating quantifiable data.

A biologist given the task of aiding in water intake design is faced with obtaining a large amount of data and information. Not all of the information is needed and some available information is incomplete. By following this manual, a biologist should be able to compile, organize, request new information, and communicate with design engineers. Data are needed that will explain how fish and shellfish integrate stimuli and behave near intakes. Development of a consistent approach to this problem will lead toward an assembly of information that will apply to the design and location of environmentally acceptable water intake structures.

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D. A. Neitzel, M. A. Simmons and D. H. McKenzie

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This manual is intended to provide guidance to the biologist who is asked to provide biological input during the construction or subsequent alteration of a water intake structure. Examples of the types of biological information that might be included in intake design are presented. Procedures for quantifying biological information and defining specific tasks that will generate quantifiable data are discussed. Procedures described apply both to new and modified water intake structures.

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